Appendix C
Seepage Failure Mode Continuum

Figure 1 was developed to illustrate the progressive nature for seepage\internal erosion failure of a dam. The failure continuum illustrates two relative and interdependent scales:

1. Stages of a seepage erosion/piping failure development, and
2. Corresponding risk reduction strategies that can be considered for implementation as the failure mode is progressing toward breach formation.

The stages of a seepage erosion/piping failure mode development as presented are generally consistent with the stages described by Foster and Fell (1999), and the US Bureau of Reclamation (2000). The stages include initiation, continuation, progression, and breach formation. The literature describing these stages is somewhat ambiguous with regard to the transition between the continuation and progression phases. It is not uncommon for these terms to be used interchangeably depending on various nuances associated with a material transport (erosion and piping) failure of an embankment dam. However, the continuum developed in Figure 1 illustrates these as two distinct and separate stages in the development of the failure mode as described further below.

Initiation: Initiation begins at the onset of a loading condition that leads to the development of a concentrated leak (e.g. raising the pool, development of a crack due to an earthquake, differential settlement, and hydraulic fracture). Initiation can also occur when seepage begins to exit a free (unfiltered) discharge face with sufficient gradient, quantity and velocity of flow so that soil particles begin to move. Initiation may occur in the embankment, in the foundation/abutment, or at the interface between the embankment and foundation materials.

Continuation: Following initiation is the continuation stage. During continuation, the pipe or erosion front moves up gradient toward the source of water and is not arrested due to the presence of a filter, cutoff, restriction or stoppage by material at the upstream end, caving because a roof does not form, or other intervention activity. The piping or erosion typically continues towards the source of water at an accelerating rate due to increasing gradients and flow quantities.

Progression: The progression phase occurs when the piping/erosion feature(s) widen and/or deepen as flows increase in the feature. Progression is enhanced when a roof continues to form and there are no other restraints to growth. The amount of flow continues to increase causing in most, if not all, cases the piping/erosion feature to grow rapidly. The progression phase follows the continuation phase and begins when there is a significant increase in the volume and velocity of flow in the erosion/pipe feature to cause it to enlarge. For example, the progression phase would begin when a piping feature breaks through the upstream slope of the core (for a dam having highly permeable shells) or the upstream shell (for more homogeneous or low permeability shell materials) of an embankment, or through foundation materials and into the reservoir. The formation of the sinkhole through the upstream slope of the dam signifies the completion of the continuation phase and the start of the progression phase of failure mode development. In some instances where overlying foundation and/or embankment materials are very stiff or well compacted, the progression stage may not manifest itself in the form of sinkhole development until significant progression has occurred.

Breach Formation: As progression continues, flow through the erosion/piping feature and the corresponding erosion of material is not arrested. Typically, the dam crest will begin to settle due to sinkhole development, localized slope instability or unraveling of the downstream slope to the point where overtopping from the reservoir begins to occur. During breach formation, the materials in the dam are eroded, widening and deepening the opening in the dam until the full contents of the reservoir are lost.

The corresponding risk reduction strategies shown on the continuum diagram have been grouped into three overall categories that generally reflect the timeframe available for intervention: long-term, short-term, and heroic (i.e., crisis management).

Long-term: The timeframe for implementation of long-term risk reduction strategies would be in the range of 1 to 5 years. Corrective actions accomplished during this timeframe would not only stop a piping/erosion failure mode development, but in general would provide sufficient safeguards that would prevent any future failure mode initiation. **Embankment dams on Karst foundations are a special consideration and long-term solutions that prevent future failure mode initiation may not be possible. In this case, long-term solutions such as cutoff walls that do not fully penetrate the formation with Karst may provide only a limited design life.**

Short-term: The timeframe for the implementation of short-term risk reduction strategies would be in the range of 1 to 3 months. In some circumstances, depending on how far along are the continuation stage and the rate of failure mode development, short-term risk reduction strategies such as grouting or construction of filters/drains and cutoffs may occur over slightly longer periods of time. Corrective actions accomplished during this timeframe are generally aimed at preventing the failure mode from reaching the progression phase and failure of the dam. Short-term strategies usually involve some form of reservoir drawdown or modified reservoir operations under reduced storage levels.

Heroic: Heroic risk reduction (crisis management) strategies are typically those that must be implemented in the range of a few hours to a few days or weeks. **Heroic actions are typically required when a piping/erosion failure mode has reached an advanced continuation stage.** The actions taken are aggressive and implementable in order to prevent entry to the progression stage, or to arrest the progression stage in its earliest period of development and usually involves a rapid lowering of the reservoir level. Corrective actions accomplished during this timeframe would stop a piping/erosion failure mode development, and provide enough time for planning, design and construction of short- and long-term risk reduction measures leading to a permanent solution that will prevent any future failure mode initiation. It should be noted that each dam is unique and the actions taken at each site will need to be tailored to the attributes of the dam and the nature of the failure mode that is developing.

Reference

Foster, M., and R. Fell, A Framework for Estimating the Probability of Failure of Embankment Dams by Piping Using Event Tree Methods, UNICIV Report (Draft), April 1999.

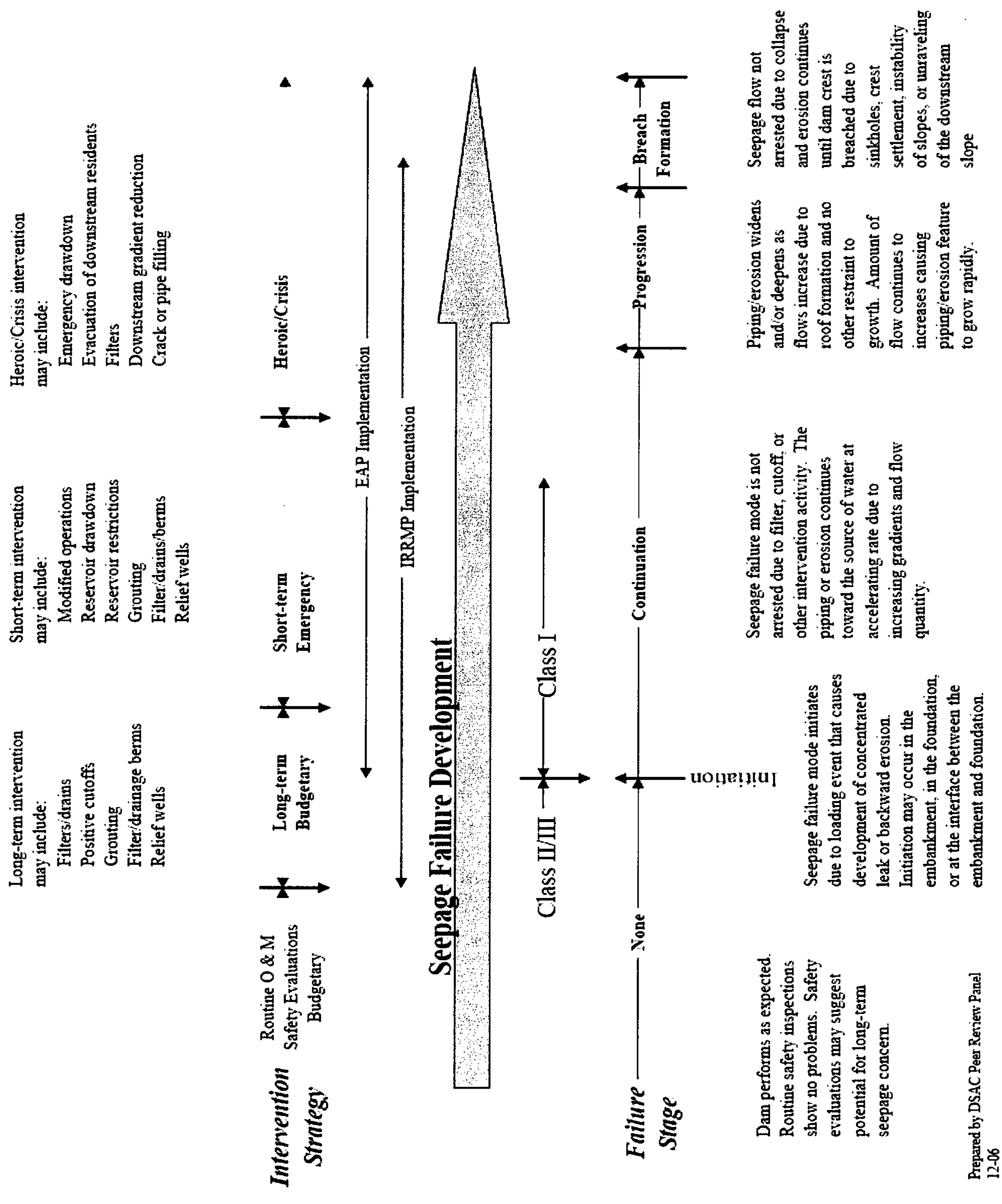

Figure 1
Seepage Failure Mode Development Continuum
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